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MICROSTRUCTURAL EVOLUTION AND MECHANICAL PROPERTIES OF MIG WELDED AA6061 ALUMINUM ALLOY

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ABSTRACT

The present investigation excretes the microstructural evolution and mechanical properties of Gas metal that arc welded (GMAW) (AA6061) aluminum alloy. The observed characteristics of fusion zone are typical coarse columnar grains structure due to the prevailing thermal conditions during the weld metal solidification. In this work, plates of 5mm thickness have been used as the base material for preparing a single pass butt welded joints by varying the current values. The filler wire used for joining the plates is AA4043 (Al-5%Si by wt.) grade aluminium alloy. From this investigation, it was found that the hardness of fusion zone was degraded significantly due to the usage of lower hardness filler metal. The involved precipitation in the heat-affected zone was characterized by XRD which improves the tensile properties of the welded AA6061 alloy.

KEYWORDS: AA6061 Aluminium Alloy, Metal Inert Gas Welding, Microstructure, Hardness & Tensile Strength

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Original Article

1. INTRODUCTION

Aluminium alloy has been considered as the most popular material for structural components in the engineering industry. The most important properties of aluminium are high specific strength and low melting point (Heinz et al., 2000, Ying and Weiping, 2005, Pharmacopoeia and Committee, 2005). Also, aluminium has an excellent corrosion resistance, high strength to weight ratio, good formability, better weldability, high electrical and heat conductivity (Davis, 1993). Several studies have been carried out in the area of joining process (Al Zamzami et al., 2019, Chen et al., 2019, Guo and Wang, 2019, Mori and Abe, 2018). Poor welding performance of aluminium alloy are likely to give a rise to the defects, such as porosity, incomplete penetration and cracking due to strong affinity of aluminium to form oxides at a higher temperature (Huang, 2010).

AA6061-T6 alloy is a special class of aluminium alloy, which is heat treatable and is very widely used in aerospace, automobile and shipping industries (Burger et al., 1995). Even with the development of solid based process such as Friction Stir Welding (Vysotskiy et al., 2019), fusion based welding technique is still widely accepted for various thicknesses and all weld positions such as horizontal and vertical. Even though the joining of AA6061 alloy using the fusion weld process remains a challenge due to the formation of intermetallic phases and crack sensitivity in the weld bead as a result of the excessive heat generation. The material experiences thermal

cycles in fusion zone (FZ), due to the heat generation during welding and cooling in the ambient condition that leads to microstructural changes. It can also induce significant changes in mechanical properties of AA6061-T6 weldment (Ambriz et al., 2010a, Ambriz et al., 2010b, Kumar and Sundarrajan, 2009, Ambriz et al., 2011). There are mainly three characteristics zone of fusion welded specimen: Fusion Zone (FZ) – This zone has epitaxial grain growth and solute redistribution which resulted in microsegregation. The solute elements were present over the dendritic arm spacing. This phenomenon affects the mechanical, corrosion, and deformation properties etc.(Singh and Flemings, 1969, Kato and Cahoon, 1986)

Heat Affected Zone (HAZ) can be divided into two subzones. One which is adjacent to the weld pool, namely HAZ-1, experiences the solution temperature (803~843 K). This temperature goes down towards the base metal. HAZ-2 zone experiences some overageing and the incoherent Mg_2Si (β) phase appear (Maisonnette et al., 2011, Ambriz et al., 2010a, Ambriz et al., 2011, Gupta et al., 2001, Edwards et al., 1998). The base metal characterized by unaffected and unaltered grain structure due to the heat generated by the welding. But some amount of residual stress was generated due to the FZ experience net contraction deformation and the unfused materials that expand freely in the transverse direction of welding.

The MIG welded joints of aluminium alloys have been studied by several authors (Torres, 2002, Miyazaki et al., 1994, Hirose et al., 1999) in terms of their bending strength, residual stress and degree of the involvement of heat resistance etc.(Liu and Yi, 2013, Riahi and Nazari, 2011). Myhr O. et.al.(Myhr et al., 2004) suggested that the welded samples shows different strength and microstructural changes due to the formation and precipitation of secondary phases in the weld zone which is attributed by high heat generation during welding. R.R.Ambriz et.al.(Ambriz et al., 2009) concluded that reduction in HAZ and uniform grain structure were developed in the fusion zone (FZ), as the result of low heat input. This reduction in thermal exposure minimizes the overaging effect of the base metal which leads to the increase in mechanical strength of AA6061 welded joint. Different types of joint strength (Ambriz et al., 2010a), the local mechanical properties using the micro-indentation (Ambriz et al., 2011) and the fatigue strength (Florea et al., 2013) were also studied.

However, very few people carried out work on the quantification of the mechanical properties in terms of heat input, which is mainly, attributed the selection of MIG welding parameters. Several works have been proposed to develop incorrelation with the process variable and their effect of mechanical properties (Dong et al., 2013, Patil and Soman, 2013, Maisonnette et al., 2011). Therefore, the purpose of this research is to characterize the microstructural feature and their influence on mechanical properties. The work is mainly focused on the heat input, microstructural feature, and formation of second phase particle, welding strength of the welded AA6061 joint and its relationship with MIG welding process parameters.

2. EXPERIMENTAL DETAILS

Experimentation was carried out on 5mm thick Plates of AA6061 aluminium alloy, which were end milled to the required dimensions of 200 mm X 100 mm. A 90□ Single 'V' groove butt joint configuration (figure 1) was used to facilitate the analysis of welding at different values of current. The initial joint configuration having a fixed root gap of 1.4 mm was obtained by securing the plates by tack welds in the roll direction with the help of spacers of 1.4 mm by MIG welding. The tacked plates were thoroughly cleaned to remove the oxide layer using wire brush followed by acetone before welding and clamped using 4 C clamps. The automatic MIG welding machine (ESAB RC-AUTO-K400) was used for welding the work

pieces at various welding currents in Direct Current Electrode Positive (DCEP) mode. DCEP mode leads to a larger amount of heat generation (approx. two-third of total heat generated) at the filler metal end. The direction of welding was backward hand with torch angle of 10 to the normal direction, as torch angle dictates the shielding gas flow direction and proper shielding of weld pool. High purity commercial-grade argon gas (99.99%) was used as the shielding gas because the formation of oxide layer which makes a protective layer causing defects in weld joint due to its high melting point. Initially, pilot runs were carried out for the various current and voltage combinations to find out the optimum process parameters like Current (I), Voltage (V), Gas flow rate(f), Root gap(S) etc.

Table 1: Chemical Composition (wt. %) of Base Metal and All Weld Metals

Composition (wt %)	Mg	Si	Fe	Cu	Cr	Mn	Zn	Ti	Al
Base Metal (AA 6061-T6)	0.8	0.61	0.32	0.27	0.16	0.08	0.02	0.02	Bal
Filler Wire Spool (Al4043)	0.05	6.0	0.08	0.11	-	0.18	-	-	Bal

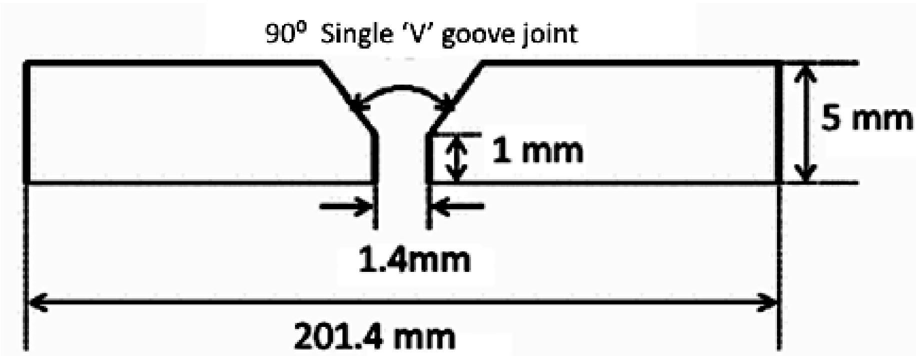

Figure 1: Schematic Diagram of Butt Joint.

MIG Welding was carried out in single-pass at variable current values of 160Amp (A-1), 170Amp (A-2) and 180Amp (A-3). Other parameters like voltage (18 Volts), gas flow rate (20l/min) and weld speed (3.5 mm/min) have been kept constant for the entire experimentation. Nozzle standoff distance was 12 mm. Welding was performed using Ø1.6 mm diameter filler wire of Al4043 grade at aforesaid welding parameters. Al4043 filler metal is an all position 5% Si alloy preferably used to join heat treatable similar alloys. It improves puddle fluidity, producing a smooth bead profile and low crack sensitivity on the magnesium-silicon aluminium alloy. Chemical composition of base metal and filler metal are presented in Table 1. The joints without surficial defects were investigated through metallography, hardness and tensile tests.

2.1 Characterization

For microstructural examination, specimens were prepared according to metallographic standard i.e. grinding (SiC emery papers) using emery paper of grit sizes 600, 800,1200,1500 and 2500 from lower to higher grade. Followed by mechanical polishing with 0.2~0.5 µm sized diamond paste along with aerosol lubricant to have a maximum conformity. The chemical etchant used was Kellers' Reagent (3 ml HF in 100 ml of water) for 20 sec to visualize the grain boundaries. The chemically etched samples were observed under an optical microscope (LeitzMetallux-3). The dendritic structure and intermediate phases in the weld bead were analyzed under Scanning Electron Microscopy (SEM) (Serial no. - EVO18-20-45, ZEISS EVO 18 RESEARCH, Germany). The grain size distribution was analyzed through ImageJ software. Hardness measurement was carried out on micro hardness tester (Model- MINIFLEX 600 DETEX ULTRA, Japan) on polished samples. A load of 300g was applied with 12s of dwell time for measurement. Indentations were taken at an interval of 0.5

mm with respect to the center of the weld bead on the surface along with the transverse section. According to ASTM E8M-04(Flat specimen) Dog-bone shaped tensile specimens of 25 mm gauge length, 6 mm gauge width and 4.5 mm gauge thickness were machined on CNC machine (EMCO Group CONCEPT MILL 260). In order to avoid the cutting effect in terms of excessive heat generation cutting fluid during the cutting process was employed. Specimens were polished in gauge length and shoulder area from 400-800 grit size emery paper. A crosshead speed of 1 mm min^{-1} was used for tensile tests on a computerized 100 kN screw-driven Instron™ Universal Testing Machine (UTM Model-4206) at room temperature. The fractured surfaces were observed under SEM. Subsized tensile specimens (for round specimen) were extracted from the weld metal region (in longitudinal direction) alone according to the ASTM E8M-04standard to analyze the all-weld metal properties.

3. RESULTS AND DISCUSSIONS

3.1 Heat input

Heat input to the weld, plays an important role in formation of the type of microstructure in weld bead, fusion zone and heat affected zone. It can be calculated using the following formula:

$$Heat\ Input(Kj/mm) = \frac{Volts\ x\ Amps}{Travel\ speed(mm/s)\ x\ 1000}$$

Microstructural feature in weld bead and HAZ is primarily governed by Heat input. Primarily with current and weld speed per unit length. Shielding gas influences the total heat input in the weld pool as it also removes the heat and ultimately affects the metallurgy of the weld joint. With an increase in heat input, there was a change in microstructure as well it can be a evident from the morphology of weld bead and HAZ from the microstructure. Samples A1, A2 and A3 have a heat input of 1.152 kJ/s, 1.224 kJ/s and 1.296 kJ/s respectively. Most influencing parameter was the current, and it governs the total heat imparted in the welding.

3.2 Microstructure

The optical microstructure of the welded AA6061 alloy was examined at different locations and it is shown in figure 3. Typically, elongated grains were observed in T-6 rolled AA6061 plate (figure 3 a). The Heat affected zone characterized by coarse and irregular grains with uniformly distributed very fine precipitates (figure 3 b). Dendritic structure in the fusion zone of MIG welded joints' fusion zone was mostly found due to the rapid heating and cooling of base metal and molten metal due to weld heat. The fusion zone of A-2 and A-3 are shown in figure 3 d and e. The only difference between the characteristic fusion zone is the dendrite arm spacing, which mainly attributes to heat input during the welding. The spacing is marginally higher as the heat input increases. The harder Mg_2Si precipitate formed during the welding, and it was observed by XRD peaks (figure 3 f). The finer precipitates were uniformly distributed (figure 3c,d,e) in the fusion zone. The precipitate coarsening was also observed as the heat input increases.

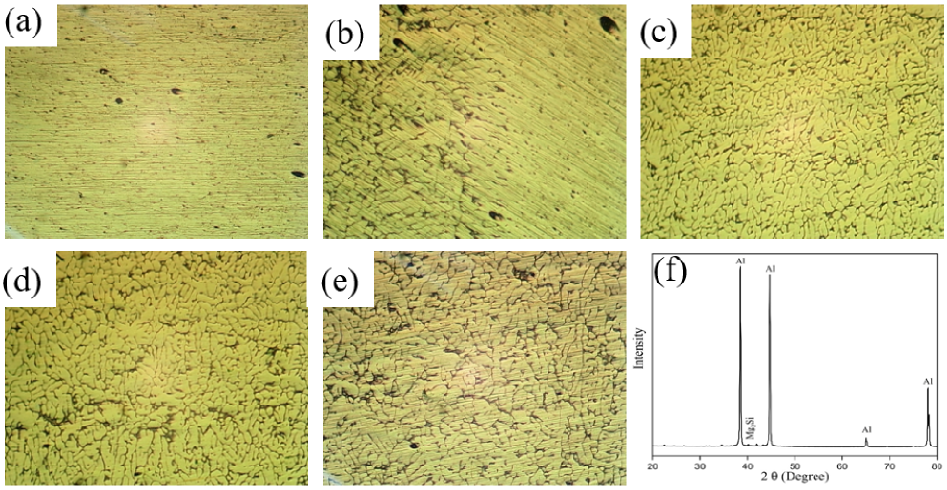

Figure 3: Optical Micrograph of (a) as Received AA6061 alloy, (b) Transition Zone (c) Fusion Zone at 160 amp (FZ (A1)) (d) Fusion Zone at 170 amp (FZ (A2)) (e) Fusion Zone at 180 amp (FZ (A3)) (f) XRD Peaks of MIG Welded AA6061 Alloy.

3.3 Hardness

The hardness across the weld cross section was measured using a Vickers Micro-hardness tester. Typical "W" shaped profile of A-1 welded AA6061 alloy is shown in figure 4 a.

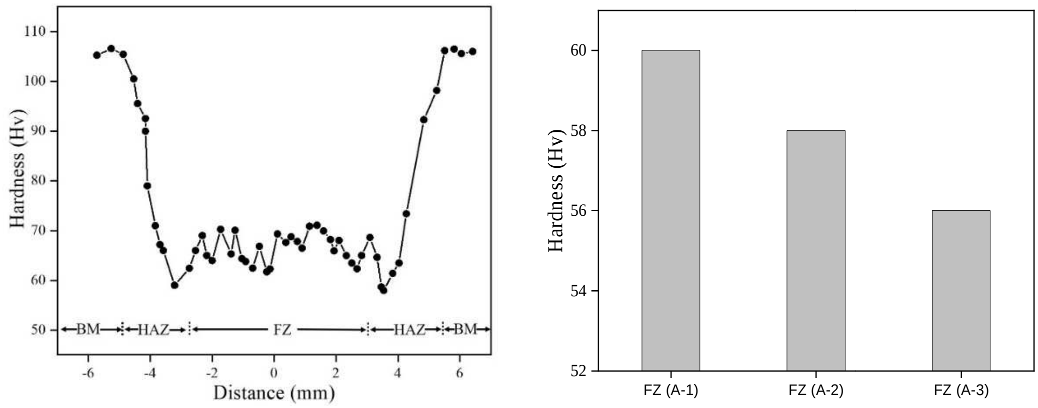

Figure 4: (a) Microhardness Profile and (b) Hardness of MIG Welded AA6061 Alloy.

The hardness of the base metal (parent metal) in its initial T6 condition is 106 VHN (figure 4b). However, the hardness of the fusion zone is 60 VHN, 58 VHN and 56 VHN for the corresponding A-1, A-2 and A-3 welded AA6061 alloy. The reduction in the hardness of the fusion zone is mainly attributed to the localized aging effect and lower hardness filler metal (Al-5%Si) used during MIG welding. This may be due to dilution of precipitates during the weld thermal cycles and material softening (Vargas et al., 2013).

3.4 Tensile Properties

The uniaxial tensile properties such as yield strength, tensile strength, % age elongation, of AA6061 aluminium alloy joints were evaluated. On each condition, three specimens were tested and the average of the three results is presented in the Table 2. The yield strength and tensile strength of non-welded parent metal are 303 MPa and 336 MPa, respectively. However, the yield strength decreased from 142 MPa to 139 MPa. While the tensile strength of MIG joints for samples

decreased from 164 MPa to 160 MPa due to higher heat input as the higher heat input soften the material. There was a reduction in ductility observed and can be evident by fractograph (figure 5). The A-1 shows superior strength among the welded AA6061 alloy due to fine and uniformly distributed precipitates.

Table 2: Tensile Properties of Welded AA6061 Alloy

Sample	Yield Strength(MPa)	Ultimate Strength(MPa)	Elongation(%)
A-1	142±2	164±4	8.5±1.5
A-2	141±3	162±5	8.2±2.1
A-3	139±3.5	160±4	7.8±1.8

The fractured surface of uniaxial tensile test specimen was observed by SEM (figure 5). The dimples formation and typical plastic flow attributed to the ductile fracture of AA6061 alloy was observed form figure 5 a. An intergranular fracture feature has been observed in A-3 MIG joints (figure 5 b).This may be attributed to the combined influence of a coarse grained weld metal region and relatively large sized precipitate formation at the grain boundaries. The fractured surface of welded AA6061 alloy also has the narrow and shallow dimples which are almost flat; thus, indicate the reduction in plastic deformation with brittle fracture. The intermetallic pullout were also observed. The dimple size exhibits a directly proportional relationship with strength and ductility, i.e., if the dimple size is finer, then the strength and ductility of the respective joint is higher and vice versa (Lin et al., 2003).

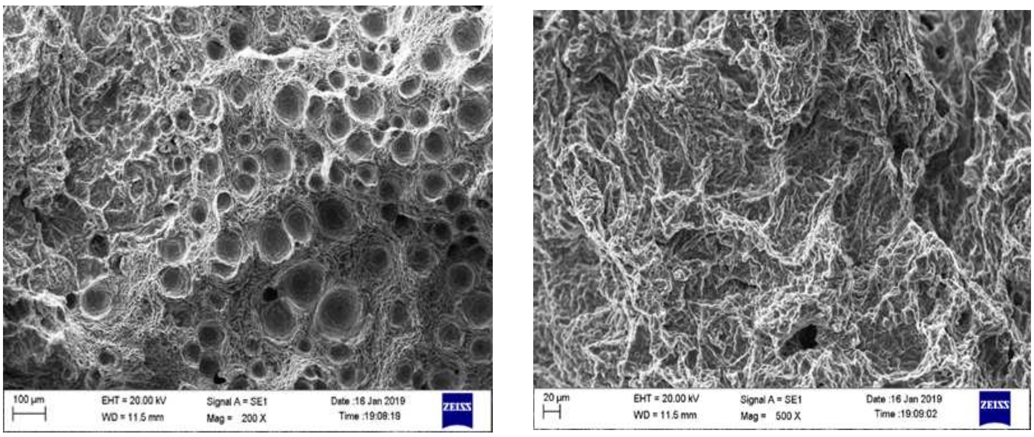

Figure 5: Fracture Surface of the (a) AA6061 Alloy (b) MIG welded AA6061 Alloy.

4. CONCLUSIONS

In this study, AA6061 alloy was welded by MIG welding. Also, the performance of the welded AA6061 alloy was judged in terms of microstructural and mechanical properties. The derived outcome from the investigation can be as under:

- Coarse and irregular grains were observed in the HAZ. The spacing between the dendrites increases as the heat input increases in the fusion zone.
- The fusion zone contains uniformly distributed precipitates.
- Hardness decreased as the heat input increased in the fusion zone due to localized ageing and material softening.
- The strength and ductility were degraded of the welded AA6061 alloy as compared to the T6 rolled AA6061 plate.
- The formation of fine and uniformly distributed precipitates (A-1) in the weld region are the reasons for superior

tensile properties among the entire welded AA6061 alloy.

CONFLICT OF INTEREST

The authors confirm that this article contents have no conflict of interest.

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